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INDUCTION FLOWMETER FOR DIELECTRIC FLUIDS

Operational Model

First Quarterly Report

by Vincent Cushing, Dean Reily, and T. R. Schein

For

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Contract NASw-381
EPCO Project No. 105

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FOREWORD

This is a report of efforts conducted during the first quarter under Contract NASw-381 for the development of an electromagnetic flowmeter for use with liquid hydrogen. The developmental work currently in progress is a sequence to prior efforts (Engineering Analysis, Contract NASr-13; Experimental Verification, Contract NASr-53) conducted for NASA by the Engineering-Physics Company.

Although the project staff feels at home with the electromagnetic flowmeter, nonetheless the newest requirement for operating with cryogenics is--for us at least--a novelty. We should therefore like to acknowledge especially the unstinted and extensive advice and practicable suggestions in these cryogenic matters provided by A. T. Bruschi of the Rocketdyne Division of North American Aviation. We should also like to acknowledge assistance bearing on instrumentation more generally as provided by I. Warshawsky and Henry Burlage of NASA.

From the EPCO staff, the mechanical design work has been carried out by Leo Di Gioia and James Griffith; the attendant electronic devices have been constructed by William Tierney; and the mechanical hardware has been fabricated and assembled by J. Richard Cullins.

Respectfully submitted,

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I. INTRODUCTION

Since December 1961 the Engineering-Physics Company has been developing, under Contract NASw-381, an electromagnetic flowmeter suitable for operational use with liquid hydrogen. The objective of this developmental effort is a flowmeter capable of passing one pound per second of liquid hydrogen, and suitable for calibration tests in the LH_2 flowmeter test facility at NASA's Lewis Research Center.

The present endeavor is predicated on recent, successfully completed work of a theoretical and experimental nature by the Engineering-Physics Company under support of Contracts NASr-13 and NASr-53. Especially during the experimental effort a great deal was learned concerning the mechanical and electronic configurations required in order to have an electromagnetic flowmeter which is operable with dielectric fluids. These same physical configurations have been utilized in the present developmental effort; and so emphasis in this report, then, is placed on those modifications in the design which are required to make the flowmeter compatible with LH_2 fluid circuits, and which are required in the interest of miniaturization, ruggedness, and simplicity.

The utility of an electromagnetic flowmeter can be established from consideration of its two unique, advantageous characteristics:

1. obstructionless flow passage;
2. no moving parts.

As is now well-known, in the EM flowmeter the fluid encounters only a magnetic field; and it is the induced EMF which produces a measurement of the flow rate. EMF measurement is made by means of detecting electrodes near the boundary of the fluid (in the design which we have formulated and successfully tested at EPCO, these electrodes do not even come in contact with the fluid, but are separated from the fluid by a thin teflon liner), and thus there is no probe or device of any kind which protrudes into the flow or disturbs the flow in any way. Thus there is no pressure drop in such a flowmeter. Furthermore, from the material standpoint, it is to be noted that the structural configuration--insofar as the flow is concerned--is simply a pipe: and with this simplicity there is today available a wide variety of chemically and physically refractive materials for especially difficult flowmeter applications. In these difficult applications (e.g., with liquid hydrogen or liquid fluorine) it is obviously advantageous to be without moving parts, bearings, etc. Finally, from the standpoint of dynamics, the lack of mechanical moving parts in the induction flowmeter provides unequaled sensitivity to flow oscillations; oscillations in fluid flow can therefore be detected and measured with limitations which are set only by the capabilities of the attendant electronic amplifier and detector.

The operability of the electromagnetic flowmeter for use with electrically conducting liquids has been well-known for many years, and indeed such flowmeters have been commercially available for use with such liquids for the past five or six years. However, there has long been an effort to make such a flowmeter operable with electrically nonconducting fluids such as petroleum base products (e.g., JP1, RP1, etc.); and very recently an effort to make the device operable with the decidedly dielectric cryogenic propellants. With electrically conducting fluids one makes use of induced conduction currents to provide the (signal) power necessary to actuate a suitable electronic voltage detector; and the novelty in the subject endeavor is that we have been able to make use of polarization currents in dielectric fluids in order to provide adequate power to actuate such an electronic voltage detector. Since it is a basic fact that polarization currents induced in a dielectric are proportional to the frequency of induction, it has been necessary to employ a high frequency magnetic field in this electromagnetic flowmeter for use with dielectric liquids. For a manifold of reasons we have for the purposes of this project compromised on an induction frequency of 10 kc per second. The perhaps determining reason is that the electronic state of the art in making quantitative, accurate voltage measurement--which is our basic objective--is limited to the audio frequency range. With some concerted electronic development effort, this frequency limit can be pushed up to 100 kc or so; but it seems imprudent to risk success unnecessarily in the subject project by becoming involved in such an extraneous effort. Actually, induction frequency requirements, as we see the situation now, are primarily determined by flow oscillation response time requirements. The present 10 kc induction frequency should easily permit 100 or 200 cycle per second resolution of flow oscillation. When flow oscillation response of, say, 1000 cps is desired, it will then be the proper time to push induction frequency up to 50 or 100 kc per second.

Theoretical considerations and the basic engineering design are as indicated earlier.[1] We describe in the ensuing pages our work to date in evolving this basic design into an operational flowmeter for use with liquid hydrogen.

II. PROJECT STATUS

In this section of the report we should like to provide some description of the work which has been carried out during the first quarter of this project--i.e., from December 1, 1961, through February 28, 1962. The items to be discussed are the following:

A. Housing and Fittings;
B. Magnet Coil;
C. Magnetic Circuit;
D. Pipe/Transducer;
E. Liquid Nitrogen Test Circuit;
F. Amplifier;
G. Magnet Power Generator;
H. Phase Sensitive Detector.

A. Housing and Fittings

During the first three months of the current project the EPCO staff gained quite valuable knowledge from several sources concerning what may perhaps be considered standard practice in the handling of LH_2. As a contractual requirement, of course, the EPCO operational flowmeter must be compatible with the LH_2 calibration facility at the Lewis Research Center of NASA. Without going into an unduly detailed discussion at this juncture we might highlight the following basic design requirements which would seem to be realistic for operation at LRC:

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[1] Vincent Cushing and Dean Reily, "Induction Flowmeter for Dielectric Fluids--Engineering Analysis," final report provided by EPCO for Contract NASr-13, March 22, 1961.

1. Flow rate of one pound per second of LH_2 (equivalent to the approximate volumetric flow of 100 gpm)--this is the maximum flow rate achievable at LRC. It would seem imprudent to design the flowmeter for less than this flow rate, particularly since future applications are almost assuredly likely to involve flow rates considerably in excess of the aforementioned value.

2. Pipe diameter of 1.5 inches--again, this diameter is chosen for compatibility with the LRC calibration facility. At the above-mentioned flow rate of 100 gpm, this corresponds to an average flow velocity of approximately 15 feet per second. This velocity is lower (by a factor of two or more) than those which are encountered with LH_2 rockets which are currently in development. This reduced flow velocity is disadvantageous for the electromagnetic flowmeter; and hence some consideration is still being given to the design of a one-inch configuration for use at LRC in order to raise average flow velocity to more realistic values.

3. Vacuum insulation--vacuum insulation is employed wherever possible in existing test installations in order to conserve the relatively costly LH_2. However, plumbing components which are proper to the rocket engine itself invariably are without such extreme insulation means, and so in the interest of compactness and light weight, consideration should be given at a later date to an electromagnetic flowmeter without vacuum jacketing. In connection with the current development effort, though, it is important to note that the LRC calibration facility operates with a maximum pressurization of approximately two atmospheres gauge. With this quite low pressure it would seem that vacuum jacketing of the electromagnetic flowmeter is a prudent precaution to minimize the possibility of flashing and consequent two-phase flow through the flowmeter. Calibration accuracy at LRC would be quite questionable, to say the least, if two-phase flow should exist in the system.

4. Explosion-proof construction--it seems that the high input impedance requirements for the amplifier of the electromagnetic flowmeter require that a vacuum tube be employed, at least in the first stage.

Accordingly, electrical potentials exist which conceivably could cause sparking if component failure should take place. Furthermore, similarly high voltages appear to be necessary--at least insofar as we know today--in order to energize a suitably strong high frequency magnetic field. Until we have developed adequate experience with this electromagnetic flowmeter it would appear best to encase all except very low voltage components in an explosion-proof housing. Indeed, in the operational flowmeter for calibration test at LRC, we plan to pressurize such a housing with a few psi (gauge) of gaseous nitrogen in order to obviate the concern for explosive gas mixtures becoming involved with sparking hazards.

We have not yet completed the detailed design of the housing and fitting configuration in the subject operational flowmeter; however, Fig. 1 is a sketch indicating the general features.

The electrical configuration for the pipe/transducer is discussed in Section II D of this report. The mechanical aspects of the pipe/transducer are as follows. The ID will be 1.380 inches in order to mate with the stainless steel tubing employed in the LRC calibration facility. The teflon liner in the new design is to project out of either end of the transducer tube in order to be flared (see Fig. 2). The flared ends of the teflon are then squeezed between the flange of the LRC steel tubing and the mating flowmeter's flange to which the flared teflon is bonded. The flared teflon end actually serves as a gasket. Its use in the present design is based on successfully tested concepts conducted by the Cryogenics Engineering Laboratory of the National Bureau of Standards.[2] With this design the teflon liner maintains its integrity throughout the entire flowmeter; and thus our attention in respect to any possible leaks may be concentrated in the area of the gasket.

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[2]D. H. Weitzel, R. F. Robbins, G. R. Bopp, and W. R. Bjorklund, "Elastomers for Static Seals at Cryogenic Temperatures," Report No. R-180 issued by the National Bureau of Standards Cryogenic Engineering Laboratory, Boulder, Colorado, pp. 6-7, 1960.

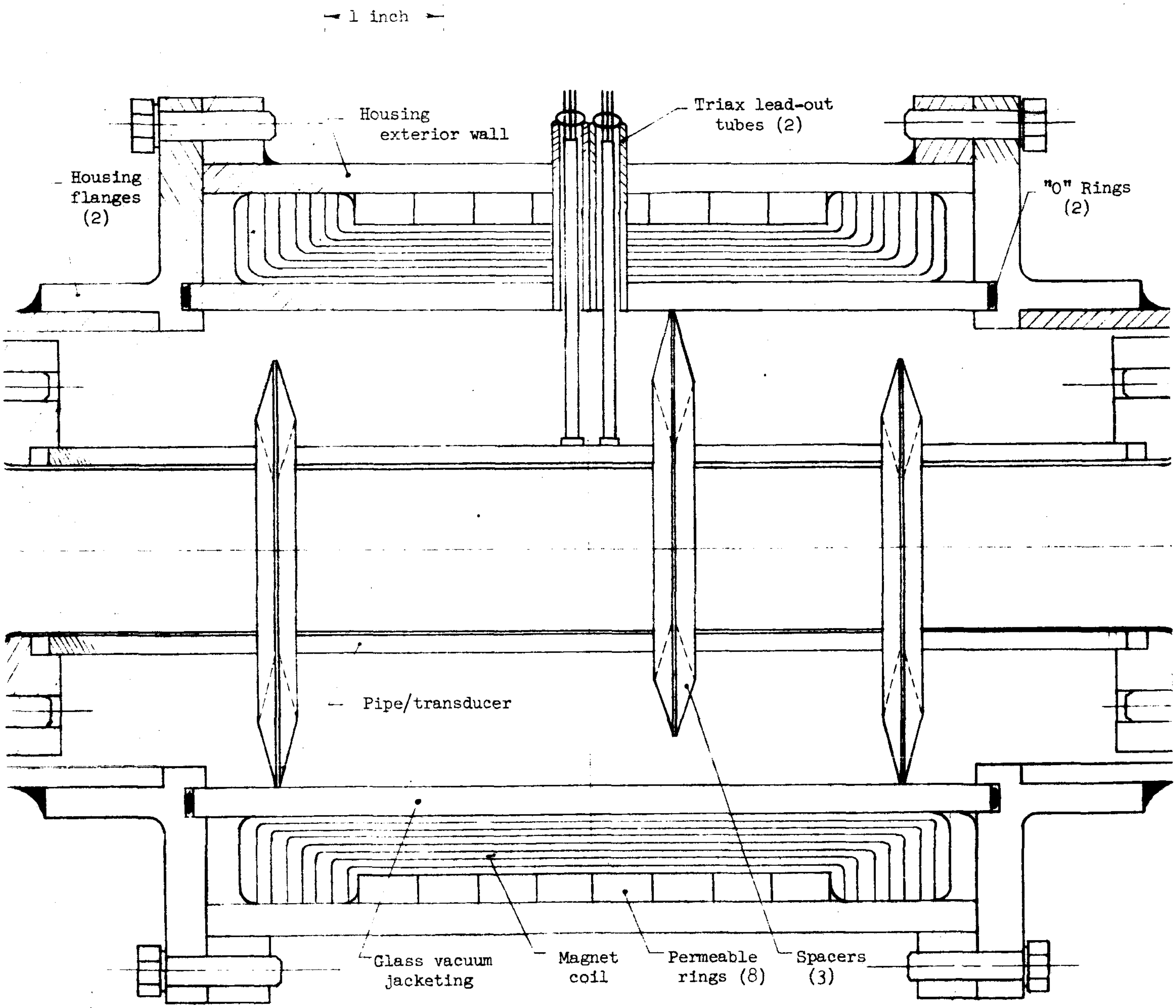

Fig. 1--General design features of electromagnetic flowmeter for use with liquid hydrogen.

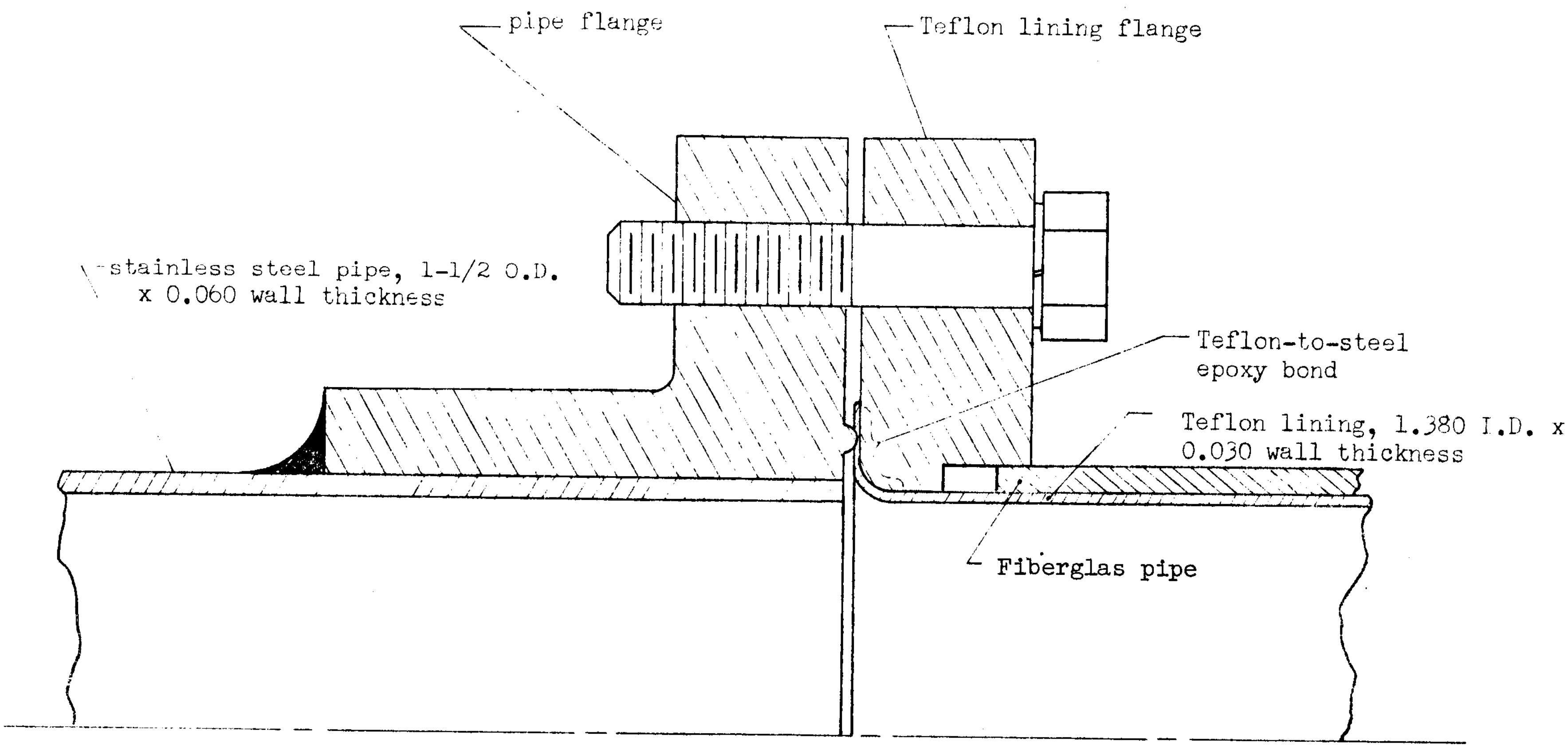

Fig. 2--Mechanical seal features of pipe/transducer for use with liquid hydrogen.

B. Magnet Coil

To date, all fluid flow measurements have been secured using cosine-wound, 114 turn coils employing a Litz weave of 100 strands of ASW No. 34 wire.[3] The individual strand insulation is high temperature polythermaleze with a single nylon overwrap. Glyptol lacquer (G.E. 1557) was used as the coil binding agent. Subsequent tests made on this coil configuration suggested possible improvement of the figure of merit (i.e., the Q of the coil) by employing a different Litz wire. Hence, two additional coil designs were advanced and fabricated consisting of 400 strands of ASW No. 44 wire insulated in the same manner as the original weave. One coil set consists of 80 turns bifilar wound, while the other design employs 36 turns of three strands 400 strands of No. 44 wire. The number of total turns varied in the three coil designs so that all three coil sets could be made to fit the same housing. The table below compares the inductance, L, and Q of the three designs at a frequency of 10 kcps.*

TABLE I

Inductance and Q of Magnet Coils
Measured at 10 kcps*

	L (mh)	Q
114 turn coil	0.91	40
80 turn coil	0.45	51
36 turn coil	0.12	25

The above data were obtained with the coils in the flowmeter housing surrounded by a sheath of carbonyl L core material (to be discussed in the next section).

As the bifilar 80 turn coil was found to have the highest Q of the configurations tested, a special Litz wire was ordered having 800 strands of ASW No. 44 insulated wire, which is practically equivalent to two strands of 400/44. Although

[3]Cf. Vincent Cushing, Leo Di Gioia, and Dean Reily, "Induction Flowmeter for Dielectric Fluids--Experimental Verification," First Quarterly Report, Contract NASr-53, October 12, 1961, p. 6.

*Made on a General Radio Bridge, Model 1650A.

the final coil design with respect to the number of turns has not been specified as yet, it has been found that the coil shape used in the tests did indeed produce a homogeneous magnetic flux transverse to pipe, whose intensity quite closely approached the theoretically derived value. Figure 3 indicates the shape of the magnetic field along the axis of the transducer. The measurements were made using a small 100 turn pickup coil covering an area of about one square centimeter.

To further decrease losses, future coils will be potted with certain silicone compounds, such as Dow sylgard 182 resin, which has much lower power factor than the glyptol currently employed.

C. Magnet Circuit

In the original flowmeter design, the magnetic return path was constructed of molybdenum permalloy rings. This material proved to be very difficult to machine, being extremely brittle. Although the permeability of this alloy is very high, it becomes hydrated after machining (and thus exposed to the atmosphere) and it appears that its resistivity thereafter drops considerably. Such lowered resistivity shows up as a correspondingly lowered Q for the entire magnet configuration. To ameliorate this problem three different carbonyl alloys, types C, E, and L, were purchased from Arnold Engineering Company and machined to size. Like the original core material the rings measure 1/2 inch thick, have an outer diameter of 3 inches and an inner diameter of 2.695 inches. The magnetic return circuit as before consists of an eight ring stack; thus having the overall desired shape of a cylinder approximately four inches long. All the carbonyl alloys machine quite well; but have relative permeabilities (μ) ranging from 20 to 40, as compared with a μ of 120 for permalloy. However, a simple calculation of the reluctance of the magnetic circuit shows that, because of the necessarily large non-magnetic portion of the magnetic circuit through the flowmeter pipe, there is little need for a μ much in excess of 10 or so in the permeable portion of the circuit.

D. Pipe/Transducer

1. Shielding--During the first quarter of the present contract, three more transducers were constructed in addition to the 3-grid, 48 turns per inch model with which flow signals were first detected during November 1961. One of

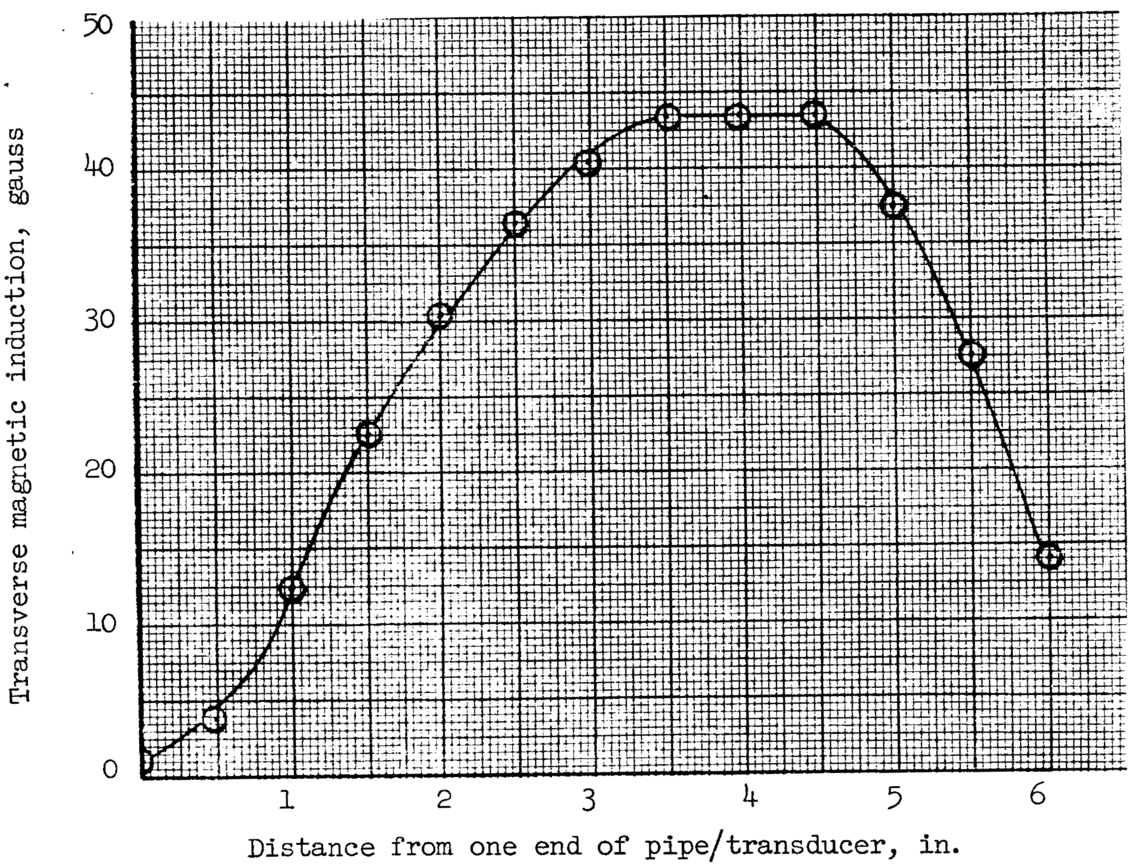

Fig. 3--Intensity of magnetic induction transverse to pipe/ transducer. Transverse intensity is plotted as a function of axial position along pipe/transducer. Entire pipe/transducer is eight inches long; detection electrodes are positioned near central, uniform region. Measurements made with 114 turn coil at 10 kc; coil applied voltage of 150 volts.

these was made by the J. Frank Motson Company using a printed circuit technique for applying the grids, and with a spacing of 10 mils between grid elements. Two additional transducers were designed and constructed at EPCO having better electrostatic shielding than their predecessor. Design of these transducers was based upon shielding factor equations as developed by Maxwell and modernly applied to grid controlled vacuum tubes.[4] Since the shielding factor is: (1) proportional to the distance between grids; (2) proportional to the grid wire diameter; and (3) inversely proportional to the spacing between elements of a grid, changes were made in the transducer spacing between elements of a grid and grid spacing to accord with this theory.

In Table II, transducer #3 had a close wound (approximately 160 wires per inch) ground grid, and transducer #4 employed two such close wound ground grids at the expense of decreasing the distance between grids. This latter design made use of the increased shielding afforded multiple grids in series. The column titled "angle (degrees)" refers to the angle subtended by the detection grid (cf. First Quarterly Report to Contract NASr-53, Fig. 6).

To measure the shielding factor experimentally the connection between the magnet coils was broken (i.e., one terminal of each coil was left open and floating) and a known alternating voltage of equal magnitude but opposite polarity applied to each half coil. The pickup voltage on the detection grids was monitored by low capacitance probes feeding matched high input impedance Keithley decade isolation amplifiers (Model 102B). During the test the driven grids in the pipe/transducer were driven with feedback voltage from the driven shield of the Keithley probes. Experimental shielding factors as used in Table II are defined as the voltage applied to the magnet coils divided by the voltage measured on the detection grids.

2. Cryogenic Tests--Part of our efforts during this quarter have been directed to understanding and solving problems dealing with material compatibility at liquid nitrogen and liquid hydrogen temperatures. This concern has

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[4] K. R. Spangenberg, Vacuum Tubes, McGraw-Hill Book Co., New York City, 1948, pp. 201-265.

TABLE II

Shielding Effectiveness for Various Ground Grid Configurations

(1) 3-grids, 48 wires per inch (original model)

Grid	Diameter (in.)	Length (in.)	Angle (degrees)	Wires/inch
detection	0.990	2.0	140	48
driven	1.375	5.0	150	48
ground	1.563	6.0	359	48

CAPACITANCE MEASUREMENTS*

Side A		Side B	
detection-driven	driven-ground	detection-driven	driven-ground
18 μμf	82 μμf	18 μμf	82 μμf

Shielding factor: 920

(2) 3-grids, 100 wires per inch (manufactured by J. F. Motson Co.)

Grid	Diameter (in.)	Length (in.)	Angle (degrees)	Wires/inch
detection	0.990	3.0	170	100
driven	1.375	5.0	170	100
ground	1.563	6.0	359	100

CAPACITANCE MEASUREMENTS

Side A		Side B	
detection-driven	driven-ground	detection-driven	driven-ground
35 μμf	130 μμf	36 μμf	118 μμf

Shielding factor: 3120

(3) 3-grids, ground grid close wound (approximately 160 wires per inch)

Grid	Diameter (in.)	Length (in.)	Angle (degrees)	Wires/inch
detection	0.990	2.0	100	20
driven	1.375	5.0	150	20
ground	1.563	6.0	359	160

CAPACITANCE MEASUREMENTS

Side A		Side B	
detection-driven	driven-ground	detection-driven	driven-ground
32 μμf	99 μμf	31 μμf	97 μμf

Shielding factor: 1332

(4) 4-grids, two concentric close wound ground grids (approx. 60 wires per inch)

Grid	Diameter (in.)	Length (in.)	Angle (degrees)	Wires/inch
detection	0.990	2.0	100	20
driven	1.144	4.0	160	20
ground #1	1.354	9.0	359	160
ground #2	1.563	6.0	359	160

CAPACITANCE MEASUREMENTS

Side A		Side B	
detection-driven	driven-ground	detection-driven	driven-ground
18 μμf	81 μμf	18 μμf	86 μμf

Shielding factor: 1000

*Capacitance measurements were made with no feedback voltage applied to the driven grid, and the ground grid floating.

led to the performance of a series of experiments which have utilized transducer materials from our past work, namely teflon, fiberglas-epoxy, and epoxy bonding resin, and the same fabricating techniques, including the formation of the copper grids.[5]

First an experiment was made to determine whether the teflon liner as bonded to the fiberglas would crack due to the difference in the linear expansion coefficients when suddenly immersed in liquid nitrogen. In this experiment no grids were bonded to the transducer pipe. After the tube had been cooled to LN_2 temperature, it was allowed to warm again to room temperature and was examined for parting at the bond interfaces and for cracks in the teflon and fiberglas. The tube was then cut in half along a longitudinal centerline to permit a closer examination of the teflon. There was no visible evidence of cracking or bond degradation. A repetition of this experiment with the tube halves still revealed no evidence of cracking or bond separation. However, it was noted that the teflon liner developed a permanent shrink slightly along its axial dimension (implying a slippage in the bond, at least near the ends of the pipe).

A second test was made, this time with a complete transducer consisting of the entire 3-grid configuration, the inner two having 20 wires per inch and the outer or ground grid being close wound (i.e., approximately 160 wires per inch). Capacitance checks made on this transducer before and after immersion in LN_2 indicated no electrical change in the grid structure. A further measurement made when the transducer was still quite cold produced no measurable deviation in capacitance values.

E. Planned LN_2 Fluid Circuit

In order that we may test cryogenically our forthcoming Model 2 flowmeter, we have undertaken to set up a liquid nitrogen test circuit. Our requirements are briefly as follows:

1. Single phase liquid nitrogen flow through our flowmeter test set-up, which is essentially a 1-1/2 inch ID pipe 5 feet in length.

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[5] Cf. First Quarterly Report to Contract NASr-53, October 12, 1961.

2. Plumbing necessary to connect our indoor test set-up with the outside liquid nitrogen storage vessel. This will require approximately 30 feet of copper pipe 1-1/2 inch ID.

3. Means of controlling the flow rate up to approximately 100 gpm while introducing a minimum of heat to the fluid system.

4. Means for determining the flow rate of the liquid nitrogen through the electromagnetic flowmeter.

Figure 4 shows a circuit diagram of the liquid nitrogen system. It consists of a 500 gallon dewar, a liquid nitrogen pump with motor and variable speed drive, a turbine type reference flowmeter, a pressure build-up system, approximately 30 feet of 1-1/2 inch copper pipes and valves as shown. It is intended that this system will be capable of producing a liquid nitrogen flow rate which can be varied up to 100 gpm. All piping and valves will be insulated with approximately 3 inches of a low density glass fiber material.

On the average we estimate that the system is likely to be in cooled-down condition approximately 1-1/2 hours per day, and the pump is likely to be in operation approximately one-half hour per day. The variable speed drive pump will be used to adjust the flow to the desired rate. Valve V_4 will be used for fine control of flow rate and of pressure in the test section, although in general it is expected that this valve will be full open.

F. Amplifier

During the period of the first quarter as reported herein, we have continued investigations with the electromagnetic flowmeter with basically the same electronic circuitry as was used during the successful experimental phase conducted under a prior contract (NASr-53). The amplifier circuit, as indicated in Fig. 5 , consists first of all of a two-stage capacitance-coupled amplifier--employing vacuum tubes V_1 and V_2--wherein the entirety of the forward gain is fed back degeneratively into the cathode of the first stage. Since our electromagnetic flowmeter provides a push-pull signal, accordingly we have employed a push-pull input to the amplifier--i.e., we have symmetrically a two-stage, feedback stabilized amplifier incorporating vacuum tubes V_3 and V_4.

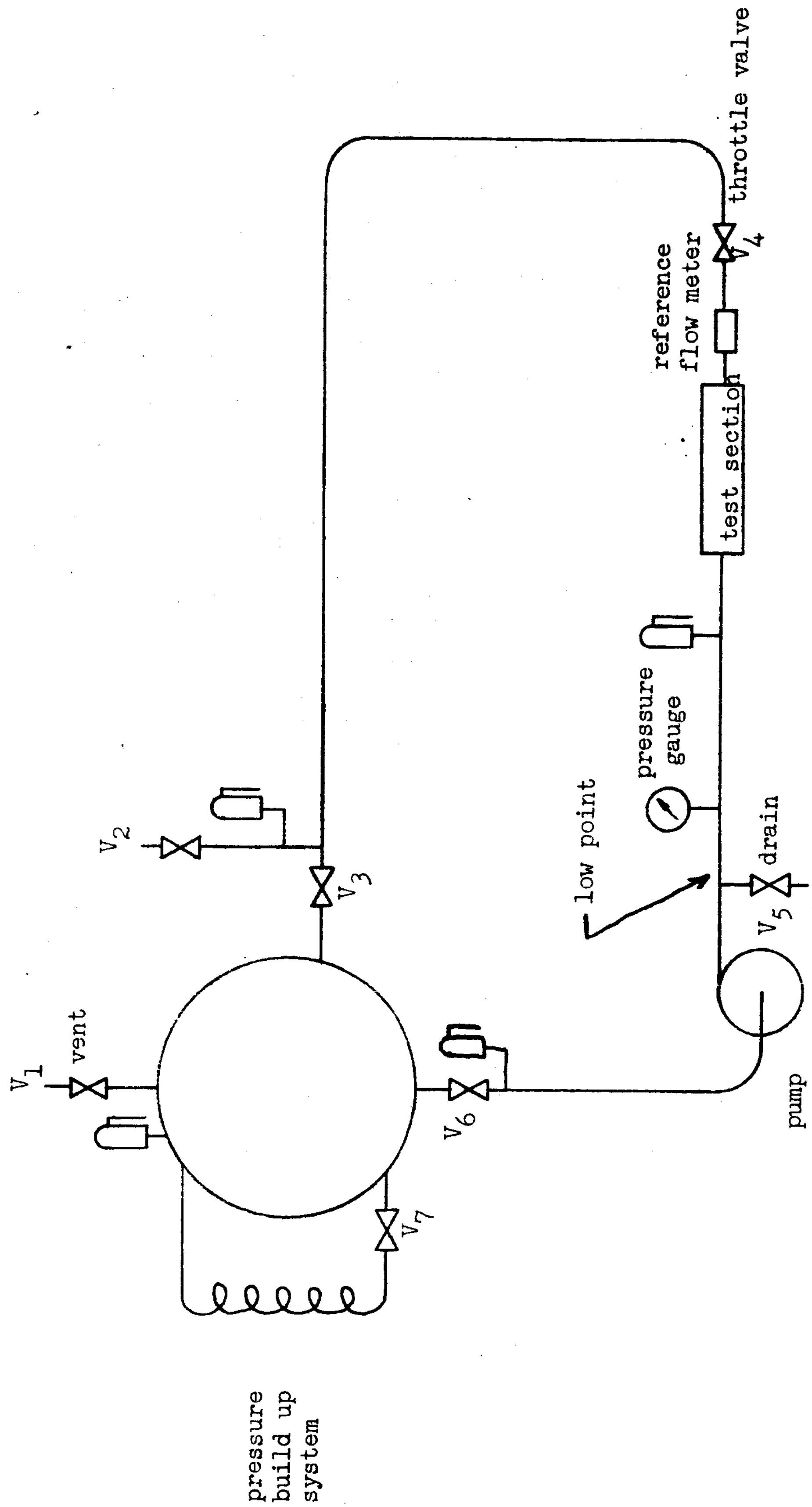

Fig. 4--Liquid nitrogen system.

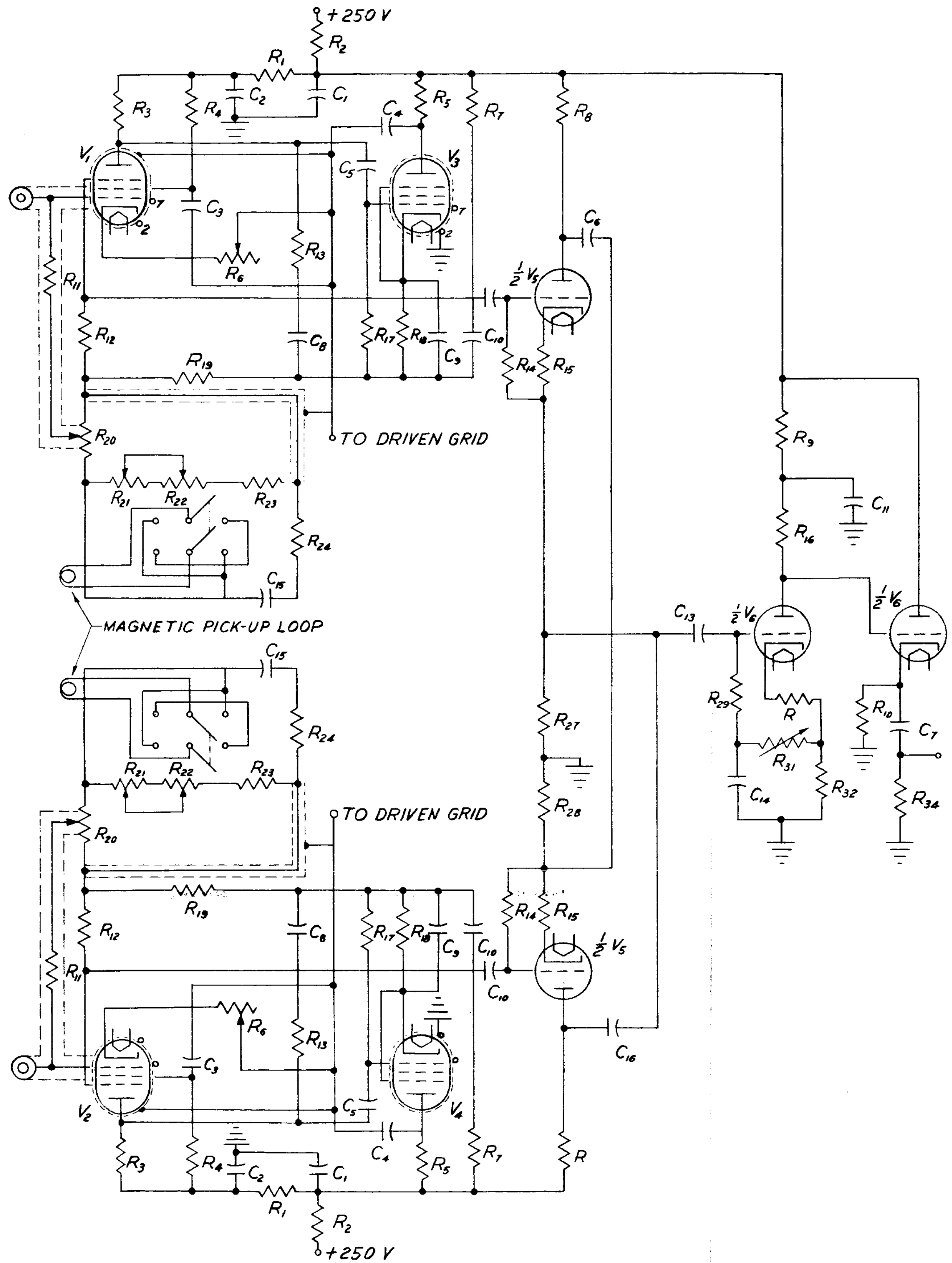

Fig. 5--Schematic of amplifier used for detection of flow signal.

R_1	27K	R_{28}	68K	C_1	150μf
R_2	2.2K	R_{29}	1M	C_2	2μf
R_3	22K	R_{30}	1.3K	C_3	2μf
R_4	220K	R_{31}	0-100K	C_4	20μf
R_5	22K	R_{32}	47K	C_5	3000μμf
R_6	0-5K	R_{33}	1.3K	C_6	4μf
R_7	68K	R_{34}	100K	C_7	1μf
R_8	68K			C_8	270μμf
R_9	15K			C_9	.01μf
R_{10}	160K			C_{10}	1μf
R_{11}	22M			C_{11}	4μf
R_{12}	2.2K			C_{12}	4μf
R_{13}	2.2K			C_{13}	.05μf
R_{14}	1.0M			C_{14}	1μf
R_{15}	1.3K			C_{15}	.01μf
R_{16}	68K			C_{16}	4μf
R_{17}	22M				
R_{18}	330Ω				
R_{19}	47K				
R_{20}	0-50K				
R_{21}	0-20K				
R_{22}	0-2K				
R_{23}	1.5K				
R_{24}	1.5K				
R_{25}	68K				
R_{26}	1M				
R_{27}	68K				

V_1 thru V_4 = EF-86
V_5, V_6 = 6112

The push-pull output of the first two stages is obtained from the cathodes of tubes V_1 and V_3. Evidently, because of the very large amount feedback employed in the first two stages, the gain of the first two stages is unity--actually being something like 0.998. This very large amount of negative feedback in the first two stages provides the desired very high input impedance; and importantly provides an effective input capacitance which is the order of 5 picofarads.

It is common practice when employing a driven shield such as we utilize in the electromagnetic flowmeter design and attendant (very short) transmission line to the input of the amplifier, to connect the driven shield to the output (i.e., connected to the cathode in our two stage amplifier) of a highly stabilized, unit-gain amplifier; again, the purpose of this driven shield is to cause a very considerable reduction in the effective value of capacitance between the transmission line and its surrounding shield. Further than this--as indicated in an earlier report[5]--if we wish to reduce the effective input capacitance of our amplifier to the ideal value of zero, this can be done by driving the shield from an amplifier whose gain is very slightly greater than unity. The net effect is that the slightly overdriven shield effectively gives rise to a negative capacitance, and this negative capacitance is adjusted so that it cancels the small natural, positive capacitance normally encountered. As shown in Fig. 5, the driven shields are therefore electrically connected to the high side of the rheostat R_6 indicated in the figure. The proper amount of overdrive on the shield may be adjusted by corresponding adjustment of the rheostat. By this technique, with the rheostat shorted out so that the driven shield is connected to the cathode of the first stage, we have, as we have already described, in the present amplifier an input capacitance of the order of 5 picofarads. However, by adjustment of the rheostat as just described, it is possible to reduce the effective input capacitance--as measured on a General Radio 1650A bridge--of our amplifier to approximately 1-2 picofarads, depending on the frequency employed. We surmise that the effective input capacitance can be reduced even further by a factor of 10 or 20, or more, if careful attention is given to the slight phase shift which may take place in our preamplifier--with the net effect that the driven shield is not driven precisely in phase with the signal voltage. However, in a fixed frequency amplifier to be developed and employed in the subject operational model, it would appear that effective input capacitance for the attendant amplifier can be reduced to a quite low value indeed.*

As discussed in the final report to Contract NASr-13[1] there is practically always a concomitant hum voltage due to the so-called transformer effect. This hum voltage is in quadrature with the flow induced signal voltage, and therefore may be rejected by the use of a phase-sensitive detector as discussed in Section II H of this report. However, if the hum voltage should be excessive, it is possible that the amplifier will be saturated before the phase-sensitive detector may be utilized; and therefore it is desirable to provide an approximate, manual hum-bucking voltage at the very input to the amplifier. By reference to Fig. 5 the proper magnitude of this hum-bucking voltage is injected into the grid of the first stage by means of the potentiometer R_{20}. The voltage which is injected at this point is originally derived from a single loop (immediately next to the pipe/transducer) which provides a voltage as induced by the alternating magnetic induction. Generally, there is a small amount of phase difference between the hum voltage picked up by this sensing loop and the hum voltage detected in the flowmeter circuit. Accordingly, a phase shift network consisting of the fixed resistors R_{23} and R_{24}, the rheostats R_{21} and R_{22}, and the fixed capacitor C_{15} is employed; the output of this phase shifting network is then fed into the potentiometer for injection into the grid of the first stage as described above.

As seen in Fig. 5 , the push-pull output of the feedback-stabilized first two stages is fed into the common mode rejector circuit built around the twin triode, V_5. This common mode rejector at the same time provides a single-sided output which is proportional to the differential input voltage to this common mode rejector stage. The output of the common mode rejector is then fed into a

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*Also, it should be mentioned that one picofarad is the limit of resolution for the General Radio 1650A bridge which we have been using; and so our measured limitation of 1-2 picofarads may be partially due to measurement limitations. For further development work the Engineering-Physics Company is procuring a capacitance bridge with a resolution in the order of millipicofarads.

conventional triode amplifier built around one half of the twin triode V_6. The output of the triode stage is in turn fed into the cathode follower circuit as shown; the cathode follower has the virtue, of course, of a quite low output impedance for transmission of the amplified flow signal over a considerable length of transmission line if desired.

The amplifier currently in use was purposely designed for test purposes with a capability for operation over a wide band of frequencies. This was deliberately done so that the operating frequency of the flowmeter could be varied between 10 and 100 kc per second, so that one could determine the best operating frequency for the final operational model. Such a wideband amplifier, as is well-known, accepts and amplifies a considerable amount of noise, including the electrical static noise which is generally generated in any flowing dielectric.

The amplifier which we are now developing is to be a tuned, fixed-frequency, gain stabilized, low noise device. For ruggedness, reliability, and compactness, transistors are employed almost throughout; however, because we require a quite high input impedance to our amplifier, and particularly a quite low input capacitance, it is necessary, at today's state of the art, to employ vacuum tubes in the first stage.

G. Power Generator

A power oscillator is required to drive the magnet coils in the flowmeter; and for our purposes thus far we have used a variable frequency ultrasonic generator having the flexibility necessary in a piece of test equipment. However, it is a considerably bulky piece of equipment and has a power output far in excess of our present needs. Now that we are more knowledgeable of our power and frequency requirements we are prompted to develop a considerably smaller operational solid state oscillator to drive the magnet coils.

Our present oscillator requirements are:

1. Power output 15 to 25 watts.
2. Frequency 10 kc per second.
3. Amplitude stability better than one per cent.

During the period reported herein, an oscillator was developed using a single power transistor in rather simple circuitry. This oscillator is shown in Fig. 6. A 2N1907 germanium power transistor* was used because of its high power and high frequency characteristics. The transistor was operated class B and a simple voltage dividing biasing network was used. In order to develop the required magnitude of alternating flux in the magnet coils, it was necessary to develop a circulating current of 4 amperes in the tuned circuit containing these coils. Such a circulating current prescribes a voltage across the coils of approximately 200 volts rms; therefore, it was necessary to develop an impedance matching network to couple the oscillator to the load.

The impedance match was obtained by transformer coupling to the magnet coils by hand winding 15 turns of No. 10/34 Litz wire around the core material on each side of the driver coils as shown in Fig. 8. Although the magnetomotive force was thus introduced in the core materials at the sides of the driver coils, the cosine winding distribution of the coils and the overall magnetic configuration forces the proper flux distribution inside the pipe/transducer. Several more turns were placed on the core material to provide the feedback loop between the base and emitter circuit.

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*Texas Instruments.

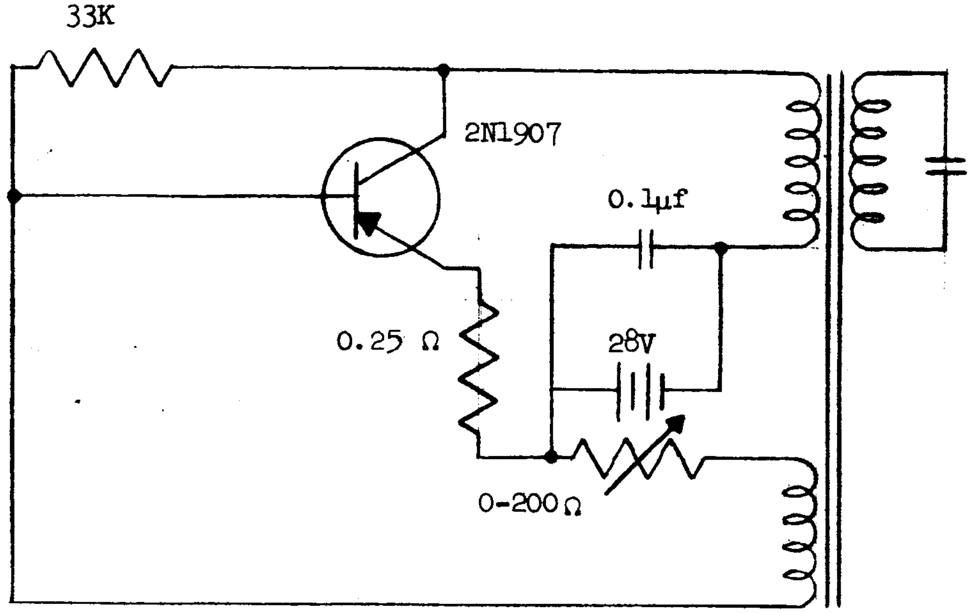


Fig. 6--Transistorized 10 kc power generator for driving magnet coils.

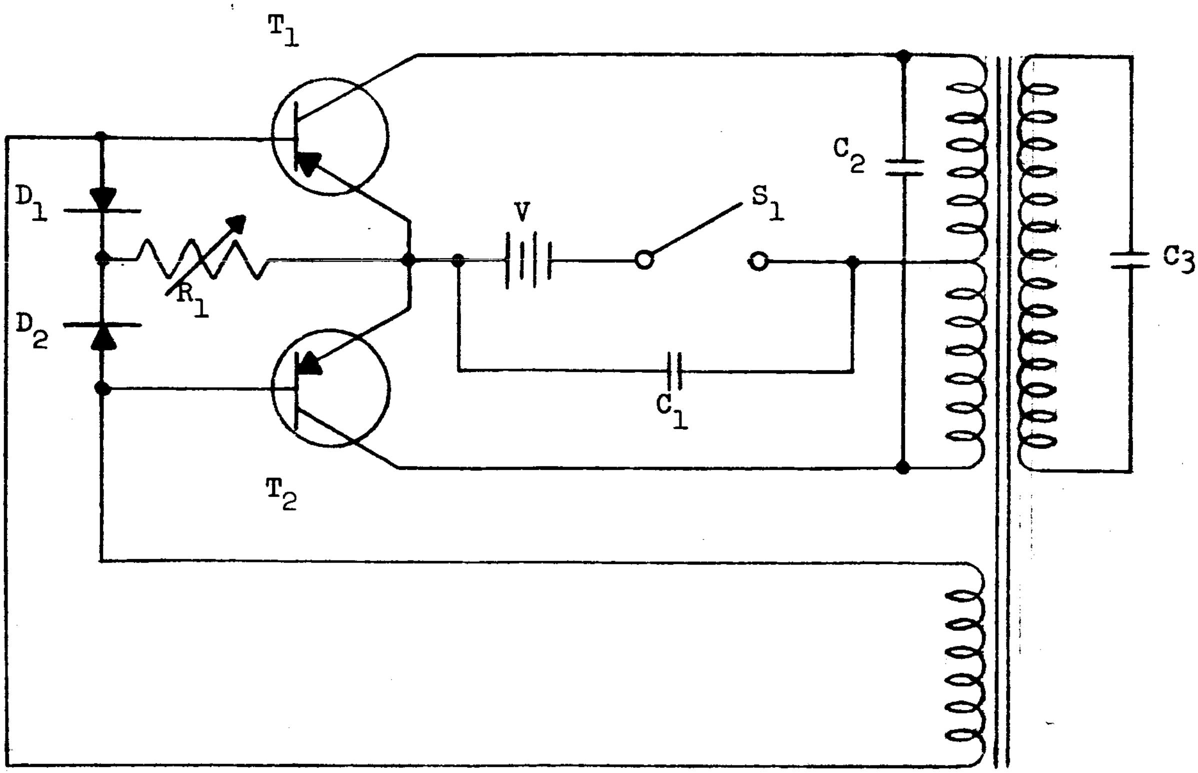


Fig. 7--Push-pull transistor oscillator with diode compensation.

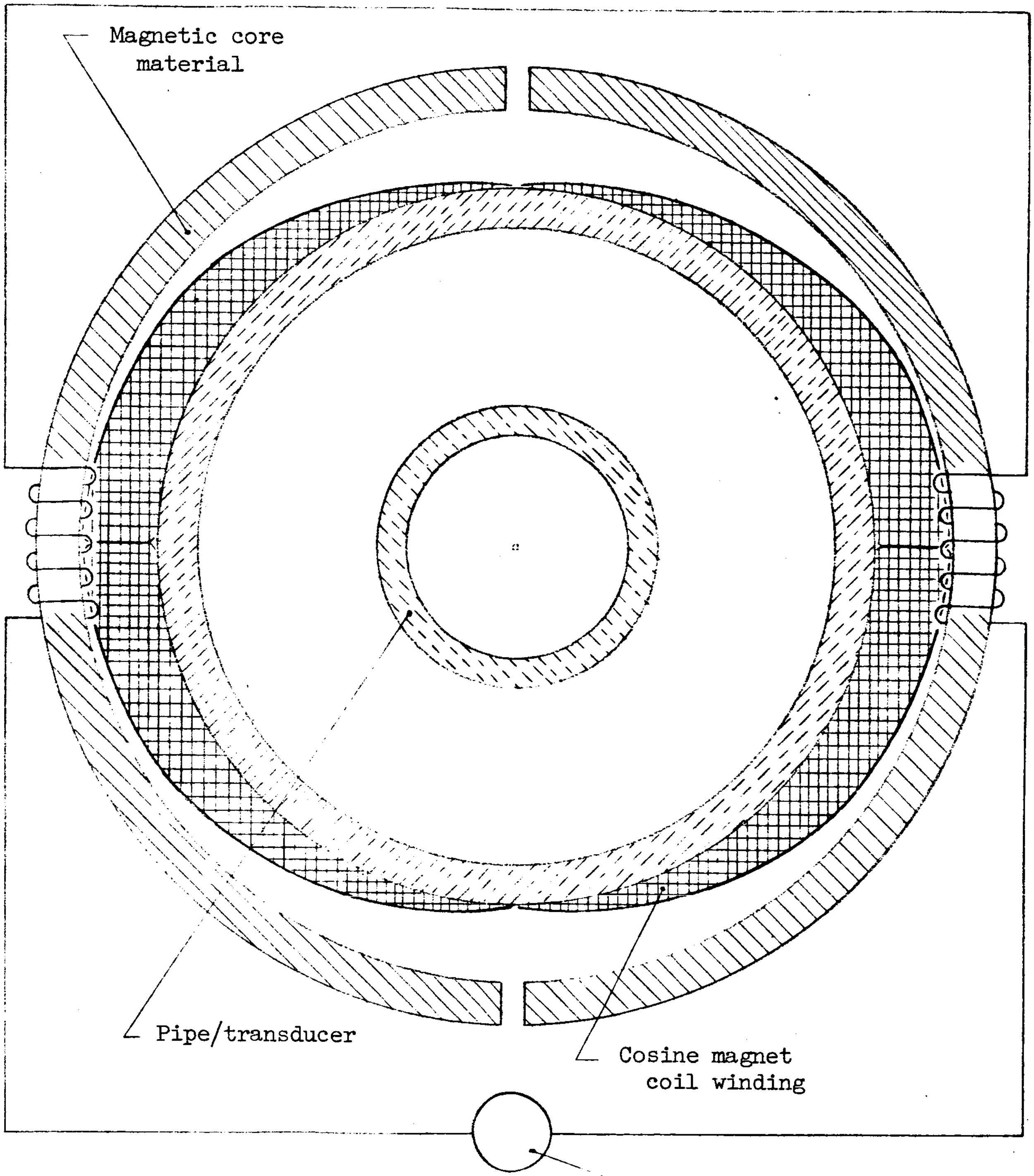


Fig. 8--Generator/magnet-coil coupling method.

Using the circuit shown in Fig. 6 and the impedance matching technique shown in Fig. 8 , the oscillator produced a circulating current of approximately 2 amperes in the tank circuit, which is essentially the driver coils in series with its tuning capacitance. This circuit could be improved considerably by changing the winding ratio of the transformer to obtain better efficiency.

A push-pull oscillator operating in class B or in class A-B has a number of advantages over the single transistor oscillator, and is more commonly used in practice. Among the advantages are increased efficiency and cancellation of the fluxes, produced by the quiescent current, which may tend to saturate the core material. Push-pull transistor oscillator design is shown in Fig. 7 . Among the improvements in this oscillator over the aforementioned one is the elimination of the voltage divider biasing network which reduces the operating range of the transistors and also reduces the overall efficiency of the stage. The variable resistor R_1 is quite small and is there for the sole purpose of providing a means of controlling the current in the tank circuit by decreasing the feedback current. The capacitor C_1 is large and provides an AC path around the power supply. The capacitor C_2 is for the purpose of suppressing surges from the primary winding which could cause damage to the transistors, particularly at the time when switch 1 is operated.

Since any modulation in the amplitude of our oscillator power supply has the same effect on our detected signal as a flow oscillation, the amplitude stability of the oscillator is important. For this reason, after the oscillator has undergone sufficient tests then, if necessary, it will be fitted with an amplitude stabilization network which may be in the form of opposing series zener diodes across the primary transformer winding or a more elegant biased diode feedback network.

H. Phase Sensitive Detector

The output signal from our flowmeter is a composite of various noise and hum voltages as well as a signal voltage. A large portion of this noise can be rejected by good filtering techniques, i.e., by use of a bandpass filter with center at the power generator frequency. Another sizeable portion of this noise can be eliminated by manual compensation, i.e., by introducing a voltage equal to the noise and 180 degrees out of phase with it. However, such manual compensation cannot be perfect (in view of warm-up drift, etc.) and there is always some remnant of the noise left. Virtually all this residual noise is in quadrature with the signal voltage and it is this portion which can be rejected by phase sensitive detection.

One very simple and attractive way of accomplishing phase sensitive detection is to use a solid state chopper. Choppers can now be obtained which will operate at frequencies of upward to several hundred kilocycles. They are very small encapsulated units. The principle upon which a solid state chopper phase sensitive demodulator works is quite simple. For example, given a noise voltage

$$V_n = A \cos \omega t \quad , \qquad (1)$$

and a flow signal voltage

$$V_f = B \sin \omega t \quad , \qquad (2)$$

where A is the amplitude of the noise voltage;

B is the amplitude of the flow signal voltage;

ω is the angular frequency;

t is the time;

we have the detected signal given by

$$V_s = A \cos \omega t + B \sin \omega t \quad , \qquad (3)$$

or

$$V_s = \sqrt{A^2 + B^2} \sin (\omega t + \theta) \quad , \qquad (4)$$

where

$$A = \sqrt{A^2 + B^2} \sin \theta \quad \text{and} \quad B = \sqrt{A^2 + B^2} \cos \theta \quad . \qquad (5a, 5b)$$

Now, if by means of our chopper and a reference signal taken from the magnet coils, we allow conduction of the signal only during the time that cos ωt is positive and with a diode allow conduction of the resultant signal only when sin (ωt + θ) is negative, then the peak voltage is given by

$$V_p = \sqrt{A^2 + B^2} \sin \left[\frac{k\pi}{2} + \theta \right] \quad , \qquad (6)$$

where $k = \pm 1, \pm 3, \pm 5, \cdots$
which from Eq. (5b) is

$$V_p = -B \quad . \tag{7}$$

A phase sensitive chopper demodulator for use with the flowmeter is shown in Fig. 9 .

The chopper to be used requires a square wave driving voltage; hence, two series zener diodes of opposite polarity in series with a resistor (to limit the current) are placed in parallel with the magnet coils as shown in Fig. 9. The clipped sine wave voltage taken from across the zener diode pair will be in quadrature (assuming that the magnet coil is a pure reactance) with the flow signal and is just that required to drive the chopper in the manner previously discussed.

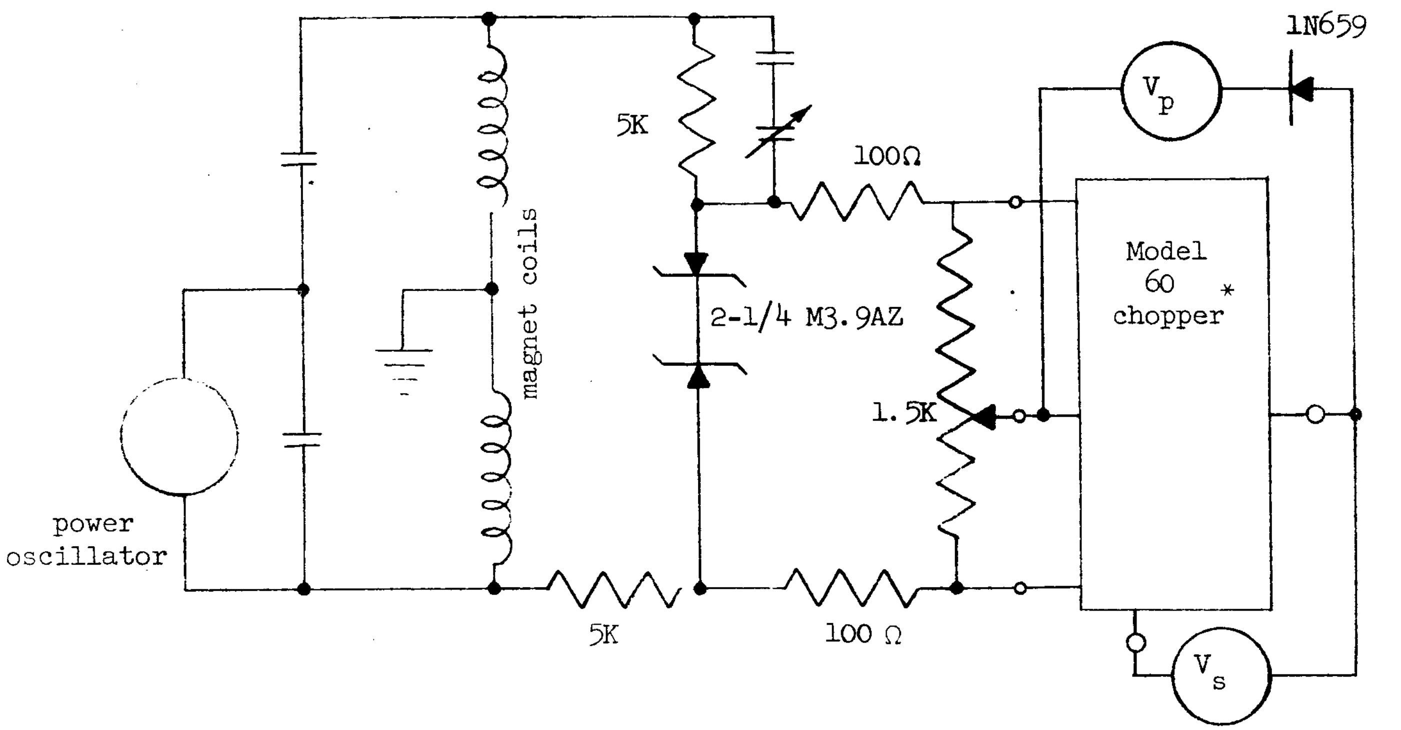
Since the instrumentation used to detect the signal is expected to introduce some phase shift, a capacitor may be placed in parallel or in series with the current limiting resistor. A fixed capacitor and a tuning capacitor, as shown in Fig. 9 will provide the necessary phase shift requirements. A voltage dividing network is used to match the impedance of the chopper.

Another method of obtaining phase sensitive detection is by the network shown in Fig. 10. Denoting our voltages again according to Eqs. (1), (2), and (3) and if we denote the reference voltage by $V_r = C \cos \omega t$ we can easily see that the output of our phase sensitive detector circuit is

$$V_o = (A^2 + B^2 + C^2 + 2C\sqrt{A^2 + B^2} \cos \theta)^{\frac{1}{2}}$$
$$-(A^2 + B^2 + C^2 - 2C\sqrt{A^2 + B^2} \cos \theta)^{\frac{1}{2}} \quad . \tag{8}$$

If we make C large compared to $\sqrt{A^2 + B^2}$ then to a first order approximation Eq. (8) becomes

$$V_o = 2\sqrt{A^2 + B^2} \cos \theta \quad . \tag{9}$$



*Solid State Electronics Co.

Fig. 9--Phase sensitive chopper demodulator.

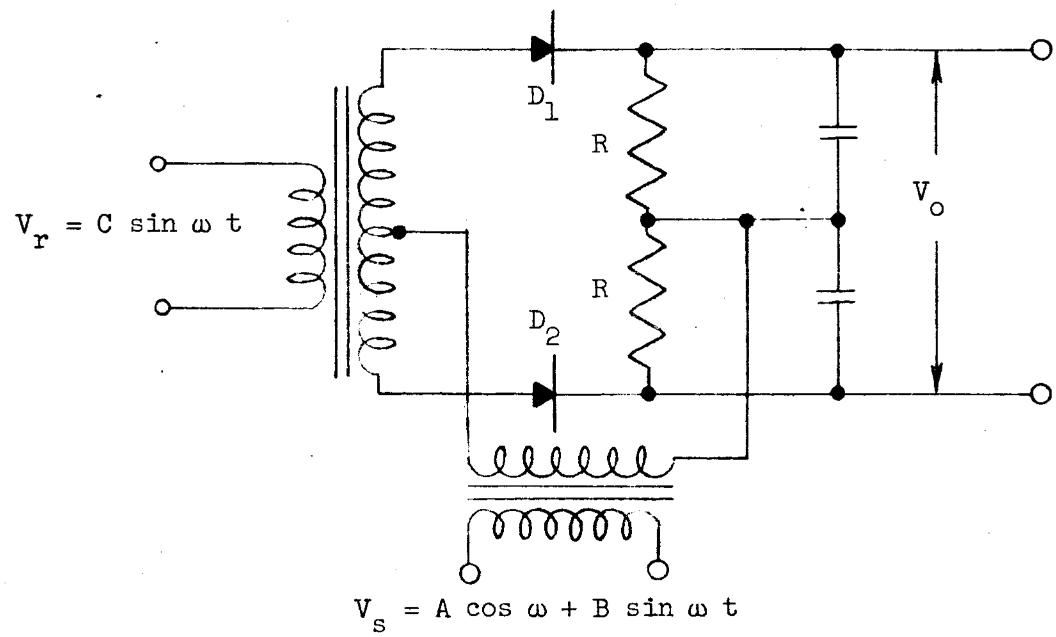


Fig. 10--Diode phase sensitive detector.

But from Eq. (5b) we have that

$$V_o = 2B \qquad ; \qquad (10)$$

hence we see that the output voltage will be twice the flow voltage. Again the same phase shifting network as was used in the chopper demodulators circuit shown previously will be needed to take care of any phase shifts which may take place in the amplifiers. A reference signal which is in phase with the flow signal is required in this demodulator; hence, if the reference voltage is taken from the coils a 90^o phase shift is required. Such a signal could be obtained by sensing the voltage across a small resistor placed in the tank circuit; however, it would be necessary to amplify this signal to obtain the large voltage required by the demodulator.

This demodulator circuit has been built and is now undergoing evaluation. As can be seen, this circuit requires the use of a number of transformers and in order for the above analysis to hold, the transformers should have a minimum of resistance and the diodes must have a very small forward breakdown voltage.

III. FUTURE WORK

The tasks we expect to conduct during the second quarter under the subject contract are the following:

1. Complete mechanical design and conduct cryogenic tests--the mechanical design of the flowmeter can be temperature shocked at EPCO by exposure to LN_2, and finally shocked in the LH_2 facility at the Lewis Research Center. Additionally, the vacuum jacketing can be leak tested.
2. Set up of liquid nitrogen fluid circuit--components have been ordered, and it appears that assembly can commence approximately May 15.
3. Complete phase-sensitive detector.
4. Complete power oscillator.
5. Develop narrow band amplifier.
6. Develop multiple power supply--as required to provide power to the several electrical components in the overall electromagnetic flowmeter.
7. Determine best shield-grid configuration for the pipe/transducer--as viewed from today's angle of vision, it appears that this is the most

critical and important task to be conducted. Attainment of an adequate shielding configuration would mean that one might expect very little in the way of troublesome, variable noise voltages getting into the flowmeter measurement system. A shielding factor of 10^6 would be desirable.

8. Build Model 2 flowmeter and test in oil circuit--in our terminology we expect to deliver, in accordance with the terms of the subject contract, our Model 3 flowmeter. The Model 2 flowmeter is our best effort today to achieve a flowmeter which will meet the requirements of the contract in all respects. However, one should be sanguine enough to believe that a test program will evidence a variety of defects and difficulties (hopefully of a minor nature). The so-called Model 2 flowmeter is built with this in mind. From experience gained with the Model 2 flowmeter, we may then be confident of making the necessary modifications in order to construct, test, and deliver the Model 3 version in satisfaction of contractual requirements.